# Effects of ICRF2 on the TRF, CRF, and EOP's

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**Abstract.** The ICRF2 became official on Jan. 1, 2010. It includes positions of 3414 compact radio astronomical sources observed with VLBI, a fivefold increase from the first ICRF. ICRF2 was aligned with the ICRS using 138 stable sources common to both ICRF2 and ICRF-Ext2. Maintenance of ICRF2 is to be made using 295 defining sources chosen for their historical positional stability, minimal source structure, and sky distribution. The switchover to ICRF2 has had some small effects on the terrestrial reference frame (TRF), celestial reference frame (CRF) and Earth orientation parameter (EOP) solutions from VLBI. A CRF based on ICRF2 shows a relative rotation of ~40 µas, mostly about the Y-axis. Small shifts are also seen in the EOP's, the largest being ~11 µas in $X_{pole}$. Some small but insignificant differences are also seen in the TRF.

**Keywords.** ICRF, ICRF2, terrestrial reference frames, celestial reference frames, Earth orientation parameters.

## 1 Introduction

ICRF was the first realization of the International Celestial Reference Frame by VLBI (Ma et al. 1997, 1998). It used VLBI data from August 1979 through July 1995. It was adopted by the IAU in 1997 and became official on 1 Jan. 1998. Its stability and precision represented an ~10 fold improvement over the previous stellar reference frame, the FK5 (Fricke et al. 1988). It initially contained positions of 608 sources, and used 212 'defining' sources to define the axes orientation. Figure 1 shows the ICRF sources. Two extensions were later made, adding 109 additional sources (IERS 1999; Fey et al. 2004).

ICRF2 (IERS 2009) was the next step. It used VLBI data through March 2009. It was adopted by the IAU in 2009 and became official on 1 Jan. 2010. It yields an approximately 5-6 fold improvement in precision and an approximately 2 fold improvement in stability over ICRF. It contains positions of 3414 sources, of which 1448 were observed in multiple VLBI sessions and 1966 in single VLBI sessions. Figure 2 shows the ICRF2 sources observed in multiple sessions. Table 1 gives a short comparison of the two reference frames.

**Table 1.** ICRF vs. ICRF2

| | ICRF | ICRF2 |
|---|---|---|
| # VLBI Observations: | ~1.6 million | ~6.5 million |
| # Defining Sources: | 212 | 295 |
| # Total Sources: | 608 | 3414 |
| Noise floor: | ~250 µas | ~40 µas |
| Axis stability: | ~20 µas | ~10 µas |

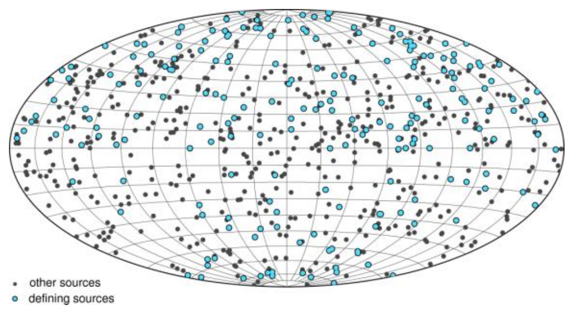


**Figure 1**. The 608 ICRF sources.

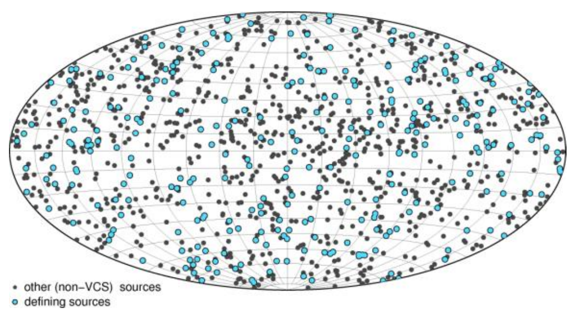


**Figure 2**. The 1448 ICRF2 multiple session sources.

VLBI improvements and the quadrupling in the amount of data from 1995 to 2009 allowed greater scrutiny of source stabilities and source structure (Fey et al. 1997). This allowed picking the most stable sources in all parts of the sky as defining sources. The ICRF2 defining sources are distributed much more evenly about the sky than were the ICRF defining sources. These two improvements eliminated the two largest weaknesses of ICRF. The

ICRF2 work showed that only 97 of the original 212 ICRF defining sources were stable enough and without significant structure to qualify as ICRF2 defining sources and only 24 of those were at southern declinations. Thus, the ICRF may not have been as stable as originally estimated.

## 2 ICRF2 vs. ICRF Based Solutions

The goal of this study is to determine the effect the switchover from ICRF to ICRF2 has on the terrestrial reference frame (TRF), the celestial reference frame (CRF), and Earth orientation parameter (EOP) results from VLBI solutions. The latest VLBI solutions are based on ICRF2 positions, whereas previous solutions were based on ICRF positions. In these solutions, the positions of the respective defining sources are initially set to their respective catalog positions. Then most, or all source positions are solved for globally with the constraint that there be no net rotation of the defining sources as a group. In ICRF2-based solutions, there is also a set of 39 'special handling' sources (the most unstable sources) whose positions are solved for as arc parameters (for each session) in order to avoid distortions of the reference frame. These solutions also usually solve for global site positions, site velocities, and daily EOP's.

## 3 Comparison of ICRF2 and ICRF Based Solutions

We generated and compared ICRF and ICRF2 based solutions to show how the switch to ICRF2 has affected the TRF, the CRF, and the EOP values from VLBI solutions. The ICRF2-based solution was our current (gsf2010a) IVS solution. The ICRF-based solution used the same solution setup and data, except that it used the 212 ICRF defining sources and their ICRF positions, and the 39 unstable special handling sources were not given special treatment. The ICRF-based solution would have been our latest quarterly solution if there were no ICRF2.

### 3.1 TRF Comparisons

The two sets of site positions and velocities were compared, and a 7-parameter fit was made to their differences (ICRF2 – ICRF). The translation and rotation differences are shown below in Tables 2 and 3.

**Table 2**. TRF Differences: Translation

| | Position (mm) | Velocity (mm/yr) |
|---|---|---|
| X-axis | -0.08 ± .17 | -0.04 ± .02 |
| Y-axis | -0.25 ± .18 | -0.04 ± .02 |
| Z-axis | +0.26 ± .16 | +0.03 ± .02 |

**Table 3**. TRF Differences: Rotation

| | Position (mm) | Velocity (mm/yr) |
|---|---|---|
| X-axis | +0.54 ± .22 | +0.05 ± .03 |
| Y-axis | +0.09 ± .21 | -0.00 ± .02 |
| Z-axis | -0.02 ± .15 | +0.02 ± .02 |

These differences are quite small. For comparison, we looked at the variations in the TRF from several quarterly GSFC VLBI (ICRF-based) solutions over the past 10 years. The differences seen among those solutions are typically an order of magnitude greater than the differences found here.

### 3.2 EOP Comparisons

We also compared daily Earth orientation parameters between the two solutions. The differences (ICRF2 – ICRF) are shown in Table 4. The EOP shifts shown here are no greater than the typical uncertainties seen in our weekly R1 and R4 sessions (last column of Table 4), and are also similar to the shifts seen between our quarterly VLBI solutions.

We also made an Allan variance study of the EOP differences between the ICRF and ICRF2 solutions compared to IGS EOP's. The Allan variances of the $X_{pole}$ and $Y_{pole}$ differences show no significant differences between the ICRF and ICRF2 values.

**Table 4.** EOP Differences

| | Shift | Drift ($yr^{-1}$) | WRMS | R1/R4 uncertainties |
|---|---|---|---|---|
| $X_p$ (μas) | 11.1±.8 | -1.8±.2 | 47.5 | ~40 – 150 |
| $Y_p$ (μas) | -4.0±.7 | 3.3±.1 | 40.5 | ~40 - 150 |
| UT1(μs) | -.5 ± .1 | .07±.01 | 2.8 | ~1.5 – 4.0 |
| $X_{nut}$(μas) | 37.6±.8 | -.4±.1 | 47.3 | ~30 – 100 |
| $Y_{nut}$ (μas) | 20.8±.8 | .1±.1 | 45.5 | ~30 – 100 |
| $X_p$ rate(μas/d) | 2.3±2.2 | .2±.4 | 125. | ~120-300 |
| $Y_p$ rate (μas/d) | -2.2±2.1 | .0±.4 | 122. | ~120-300 |
| UT1 rate(μs/d) | .05±.09 | -.01±.02 | 5.2 | ~4 – 10 |

### 3.3 CRF Comparisons

The source catalogs from the two solutions show a small relative rotation. Using 1167 common sources, we get the following rotation angles, shown in Table 5.

**Table 5.** CRF Differences

| | |
|---|---|
| X-axis | +17.8 ± 0.5 µas |
| Y-axis | -38.8 ± 0.5 µas |
| Z-axis | +3.6 ± 0.4 µas |

This rotation represents a difference of ~1.5 times the estimated ICRF/ICRF2 axis stability. Though not significant, it merits further investigation and explanation.

## 4 ICRF2 Alignment with ICRF

ICRF2 came from the gsf008a solution, which was an ICRF-based solution. ICRF2 defining sources were selected based on positional stability, low structure index (Fey and Charlot, 1997), and sky distribution. It was desired to align the ICRF2 defining sources with the ICRF defining sources. However, there were only 97 common defining sources and 73 of those were in the northern half of the sky. To improve the distribution of sources used for alignment, an additional 41 ICRF2 defining sources were selected. All had ICRF-Ext2 positions and 35 of them were at southern declinations. Thus, ICRF2 is considered to be aligned with ICRF-Ext2. The rotation angles applied to gsf008a to obtain ICRF2 (IERS 2009) are very similar to those found in this study (Table 5).

## 5 ICRF Stability

We compared several ICRF-based source catalogs from quarterly GSFC TRF/CRF/EOP solutions over the past 10 years. These catalogs were from the following solutions:

- 2000a – ICRF-based (oldest quarterly)
- 2002c – ICRF-based.
- 2005b – ICRF-based.
- 2007c – ICRF-based.
- 2009a – Last ICRF-based quarterly
- 2010a – First ICRF2-based quarterly)

Comparing 2010a (first ICRF2-based quarterly) to 2009a (last ICRF-based quarterly), we get the following relative rotation (Table 6).

**Table 6.** Quarterly CRF Differences, ICRF2 vs. ICRF

| | X-axis (µas) | Y-axis (µas) | Z-axis (µas) |
|---|---|---|---|
| 2010a/2009a | +18.1± .8 | -38.8 ± .8 | +6.2 ± .6 |

And between the various ICRF-based quarterly solutions, we get the following relative rotations (Table 7).

**Table 7**. Quarterly CRF Differences Among ICRF solutions

| | X-axis(µas) | Y-axis (µas) | Z-axis (µas) |
|---|---|---|---|
| 2009a/2000a | -37.6 ± 4.9 | +49.5 ± 4.9 | +1.9 ± 4.0 |
| 2009a/2002c | -34.7 ± 3.5 | +18.8 ± 3.5 | -6.1 ± 2.8 |
| 2009a/2005b | +3.6 ± 2.2 | +17.5 ± 2.2 | +15.1 ±1.8 |
| 2009a/2007b | -18.6 ± 1.6 | +21.0 ± 1.6 | +7.0 ± 1.3 |

The rotation seen between the ICRF2-based solution and the ICRF-based solution is similar in magnitude to the quarterly differences and does not appear unusual in comparison.

Only 97 of the 212 ICRF defining sources were found to be stable enough to be ICRF2 defining sources and only 24 of those are at southern declinations. Thus the original axis stability estimate for ICRF (~20 µas per axis) may have been over-optimistic. ICRF2 is expected to show greater stability, because of the expected improved stability and more even distribution of its defining sources.

## 6 ICRF2 vs. ICRF-Ext2 Comparison

Because ICRF2 was aligned with ICRF-Ext2 (and not strictly with ICRF), two additional solutions were made. The first solution held all ICRF2 sources fixed (not solved for) to their ICRF2 positions (except the special handling and VCS sources). The second held all 717 ICRF-Ext2 sources fixed to their ICRF-Ext2 positions. Table 8 shows a comparison of their EOPs. The overall shifts are very small here and are all less than the typical uncertainties in the EOP values.

**Table 8.** EOP Differences, ICRF2-fixed vs. ICRF-Ext22-fixed

| | Shift | Drift (per yr) | WRMS |
|---|---|---|---|
| Xp (µas) | -4.1 ± 0.7 | -9.1 ± 0.1 | 43.4 |
| Yp (µas) | 1.7 ± 0.5 | 1.4 ± 0.1 | 28.1 |
| UT1 (µs) | -1.7 ± .03 | -0.5 ± .01 | 1.8 |
| Xnut (µas) | 0.1 ± 0.5 | -1.4 ± 0.1 | 32.1 |
| Ynut (µas) | 8.3 ± 0.5 | -1.3 ± 0.1 | 27.6 |
| Xp rate (µas/d) | 1.2 ± 1.5 | -0.2 ± 0.3 | 87.5 |
| Yp rate (µas/d) | -3.1 ± 1.3 | 0.6 ± 0.2 | 79.8 |
| UT1 rate (µs/d) | 0.24 ± .05 | -.03 ± .01 | 2.8 |

## 7 Conclusions

In the switchover to ICRF2, differences in the terrestrial reference frame are very small, and less than has been seen between various VLBI quarterly solutions over the past 10 years. There are some small systematic EOP differences seen, but again, these are no larger than the differences typically seen between various quarterly solutions. There are also some small rotations seen in the celestial reference frame solutions. This is primarily a result of the two weaknesses of ICRF – the lack of stability of many of its defining sources and their uneven sky distribution, which prevented a strict alignment of the two respective sets of defining sources. ICRF2-based CRF solutions can be expected to show greater stability in future solutions than was seen for ICRF-based solutions.

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